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Identification of a Novel "Fishbone" Structure in the Dendritic Growth of Columnar Ice Crystals

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Abstract. Ice crystals growing in highly supersaturated air at temperatures near -5 C exhibit a distinctive, nonplanar dendritic morphology that has not been previously documented or explained. We examine this structure and identify its most prominent features in relation to the ice crystal lattice. Developing a full 3D numerical model that reproduces this robust morphology will be an interesting challenge in understanding diffusion-limited crystal growth in the presence of highly anisotropic surface attachment kinetics.

[The figures in this paper have been reduced in size to facilitate rapid downloading. The paper is available with higher resolution figures at http://www.its.caltech.edu/~atomic/publist/kglpub.htm, or by contacting the author.]

1 Ice Dendrites

Ice crystals growing in supersaturated air exhibit a remarkably rich variety of morphological structures, including the many different types of snow crystals that are commonly observed in the atmosphere [1, 2, 3]. These different structures result from a complex interplay of diffusion-limited growth and anisotropic attachment kinetics, and much of the surface physics that is ultimately responsible for the observed morphological diversity remains poorly understood [4].

At high water vapor supersaturations in air near one atmospheric pressure, ice crystals tend to grow in complex dendritic structures. At temperatures near -2 C or near -15 C, fern-like dendritic branching is the norm, and such structures have been studied for several decades in the context of diffusion-limited growth [5, 4]. Ice crystal dendrites at these temperatures are essentially two-dimensional, with the entire branched structure confined mainly to a single plane. The growth directions of the branches and sidebranches are also typically well aligned along the a-axes of the ice crystal lattice.

In contrast, ice dendrites growing in highly supersaturated air near -5 C have a markedly different dendritic structure that includes nonplanar branching along growth directions that are not aligned with respect to the ice crystal lattice. Examples are shown in Figures 1 and 2. We observed these structures near -5 C whenever the supersaturation was sufficiently high – typically greater than 100-200 percent [6]. We have come to refer to them as "fishbones" for rather obvious reasons. These structures are quite robust in that small changes in temperature or supersaturation do not change the overall morphology, although the angles between the various growth directions do depend on temperature and supersaturation. These dendrites are quite easy to produce in water vapor diffusion chambers [7, 8], and it is likely they have been observed by a number of researchers for several

decades. To our knowledge, however, the basic features of this crystal morphology have not been previously identified.

The relationship between the growth directions of the different dendritic features and the underlying ice lattice was not immediately apparent, and we found it useful to definitely establish the crystal axes in our experiments. We did this by first growing "electric" ice needles with stellar crystals on their ends, as described in [6] and shown in Figures 3 and 4. Unfortunately, still photographs do not easily convey the character of these complex structures, and their three-dimensional morphology is best appreciated by rotating a single specimen while viewing it with a stereo microscope.

2 A Geometrical Model

Once we established the crystal axes with certainty and viewed a number of growing dendrites under different conditions, we were able to create a geometrical model of their structure, as shown in Figures 5, 6, and 7. This model nicely fits all our observations and shows how the three-dimensional dendritic structure arises from the intrinsic hexagonal symmetry of the ice crystal lattice.

It seems possible that our single-crystal fishbone dendrites could be misidentified as the polycrystalline "spearhead" structures described in [2]. The distinctive fishbone sidebranching would be less apparent at lower supersaturations, giving the two forms a quite similar appearance. Further investigation of the fishbone morphology as a function of temperature and supersaturation, including observations of the transition from columnar to plate-like dendrites, would elucidate this further.

At present we have no clear constraints on the various growth angles in our geometrical model, as these depend on growth conditions and are tied to the highly anisotropic surface attachment kinetics inherent in ice crystal growth. Numerical techniques using cellular automata are capable of modeling the diffusion-limited growth of realistic faceted dendritic structures in three dimensions [9], but the required input physics remains quite uncertain [10].

We believe it will be an interesting challenge to create a numerical growth model that reproduces the morphology of fishbone dendrites. On one hand, this overall morphology is robust with respect to rather large changes in growth conditions (which is also true for -15 C dendrites), so we expect that models would reproduce the overall fishbone features even without a perfect parameterization of the input physics. On the other hand, the fishbone structure is sufficiently complex that significant advances in our physical understanding of the numerical models may be required. In any case, comparing theoretical models with quantitative measurements of growing dendrites will likely shed light on the presently enigmatic molecular dynamics that governs ice crystal growth.

References

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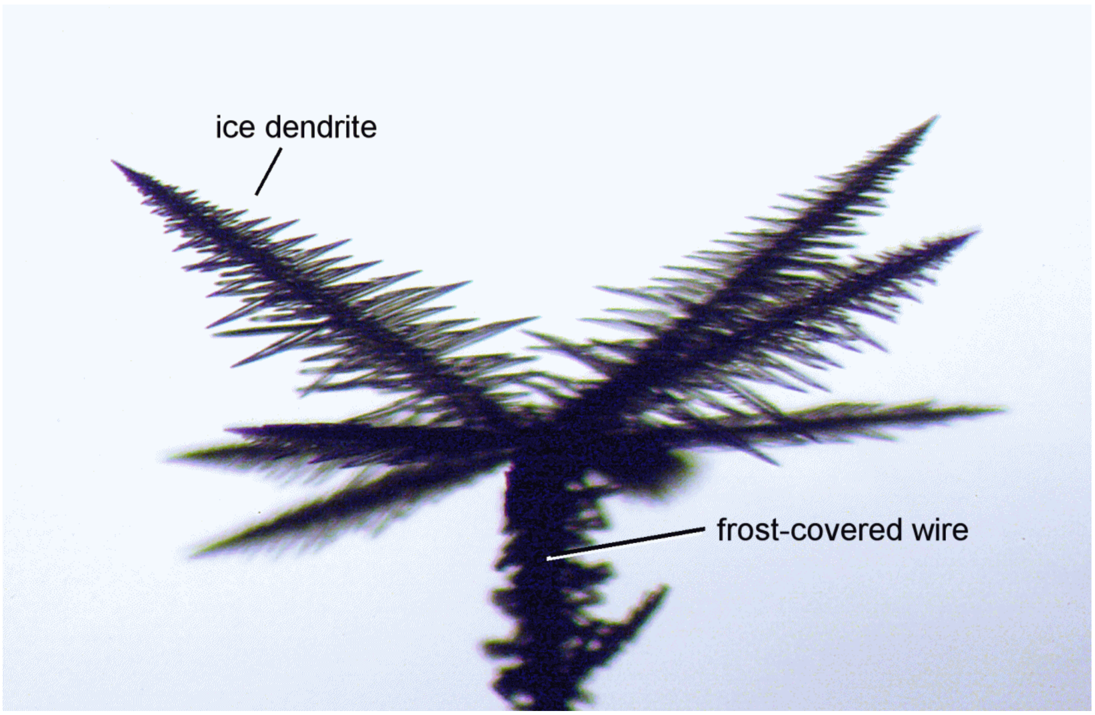

Figure 1: Ice dendrites growing near -5 C. These crystals were grown at a temperature near -5 C in a water vapor diffusion chamber. The supersaturation was estimated to be roughly 100-200 percent in the absence of any growing crystals. This photograph shows several ice dendrites, each about 2 mm in length, growing in various directions from a frost-covered wire inside the chamber. The growth rates of the dendrite tips were about 10-15 μm/second [6]. Each of the dendrites is a single ice crystal, with a fixed lattice orientation throughout the main branch and the numerous sidebranches. The eight dendrites seen in this image are separate crystals that nucleated at different points on the wire and thus are oriented randomly with respect to one another.

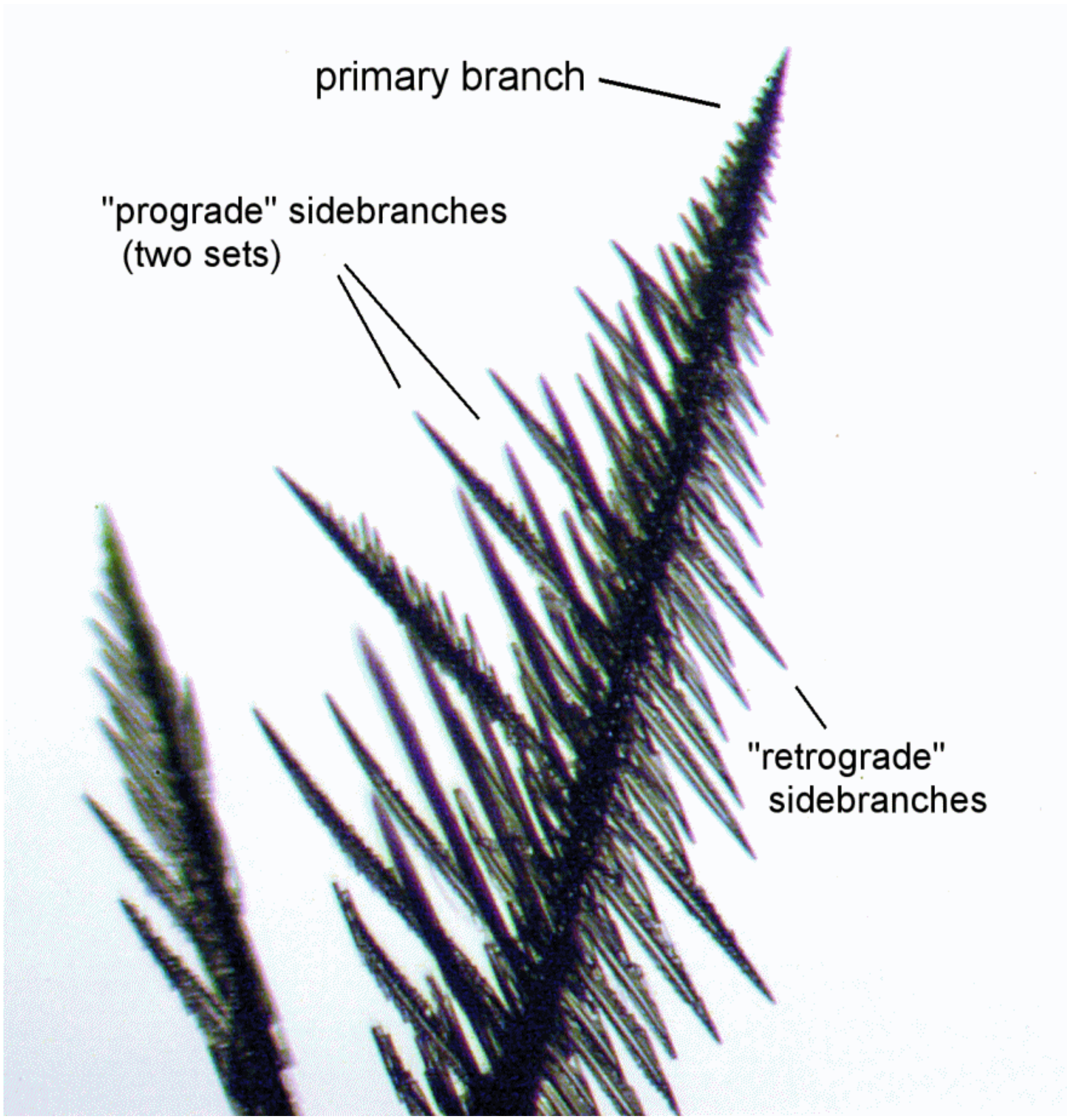

Figure 2: A closer view of a single ice dendrite growing near -5 C. As is typical for the diffusion-limited growth of dendritic structures [5], the primary branch grows outward with a nearly constant tip velocity. For growth from vapor, the tip velocity is approximately proportional to supersaturation [6]. Two sets of "prograde" sidebranches grow out from the primary spine, along with one set of "retrograde" sidebranches. The angle between the growth directions of the prograde sidebranches and that of the primary spine is less than 90 degrees; the angle between the retrograde sidebranches and the primary spine is greater than 90 degrees. The two sets of prograde sidebranches lie in two separate planes, and the angle between the planes is typically less than 60 degrees. The growth directions of the different features depend on both the temperature and supersaturation inside the growth chamber. These dendritic structures are quite robust in that they are the normal growth forms near -5 C when the supersaturation is high.

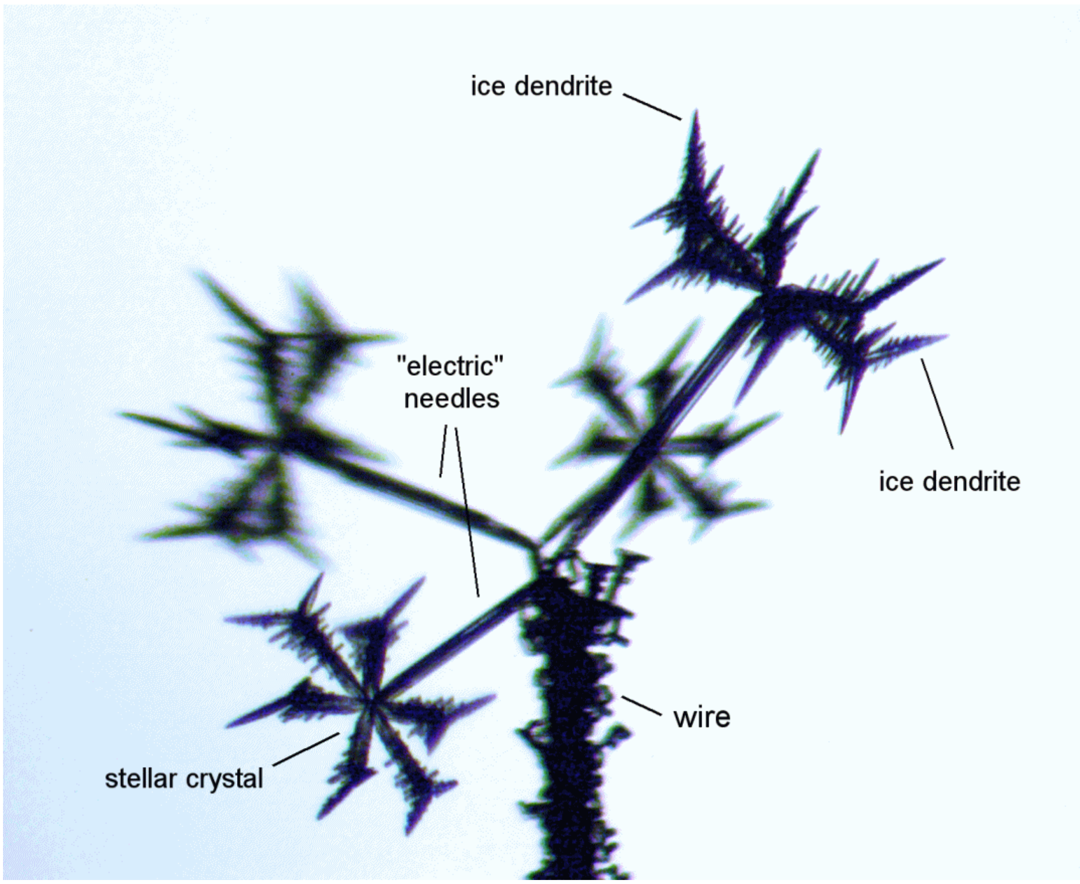

Figure 3: Defining the crystal axes. Beginning with a frost-covered wire, we first grew "electric" needle crystals as described in [6]. These needles were grown in the presence of trace chemical impurities in the air, which produced needles growing along the c-axis of the ice lattice [6]. Once the needles had grown out, we then removed the applied high voltage and moved the assembly to a separate diffusion chamber, where growth at -15 C produced a stellar plate crystal on the end of each needle. The supersaturation was relatively low in this second chamber, so each stellar crystal had six primary branches with little sidebranching. From there we moved the assembly back to the first chamber, where fishbone dendritic structures at -5 C grew from the tips of the stellar crystals. The level of chemical impurity was quite low throughout the experiment, and the impurities seemed to have a negligible affect on the normal growth of the fishbone dendrites, other than perhaps shifting the growth angles slightly.

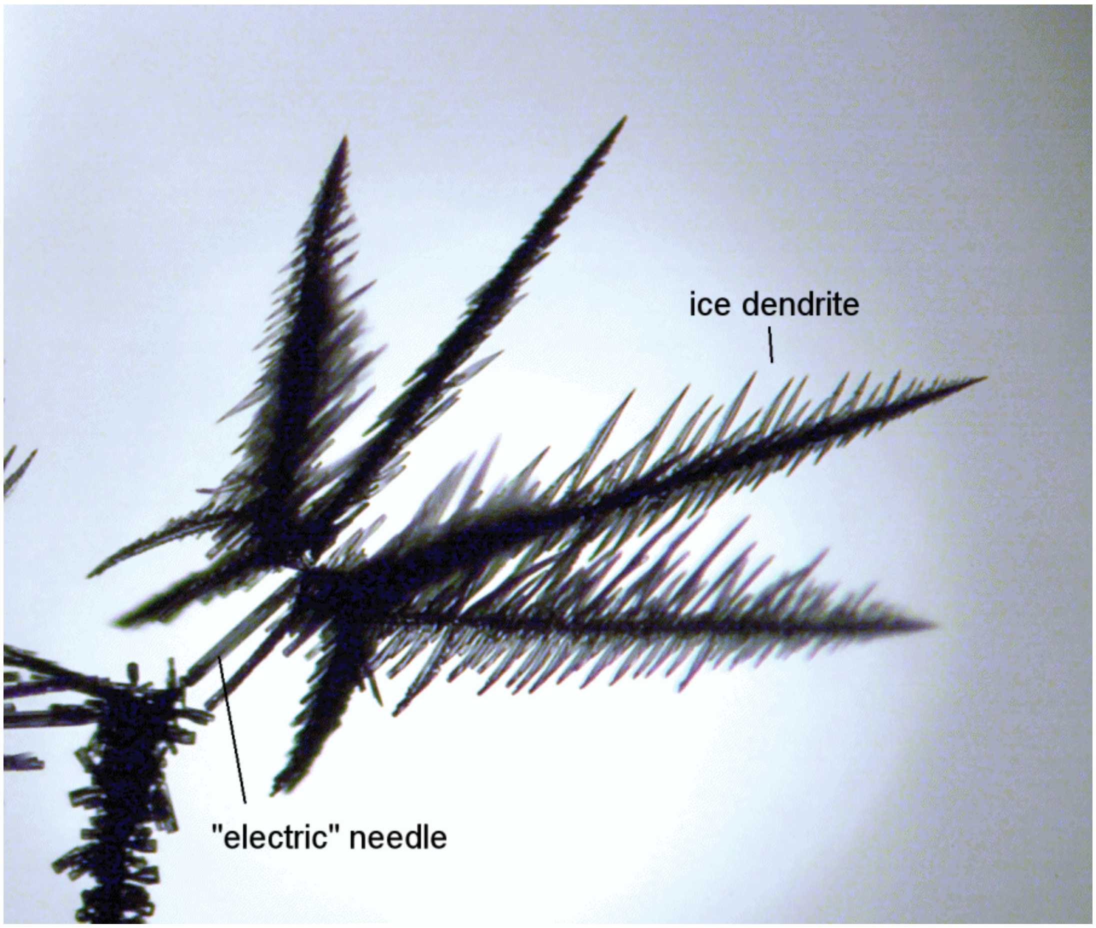

Figure 4: Similar to Figure 3, but with a closer view of the growth from a single stellar crystal, after additional growth time. Fully developed fishbone dendrites are growing out from each of the six branches of the stellar crystal (although two dendrites are not clearly visible in this image). The prograde and retrograde sidebranches are apparent on each dendrite.

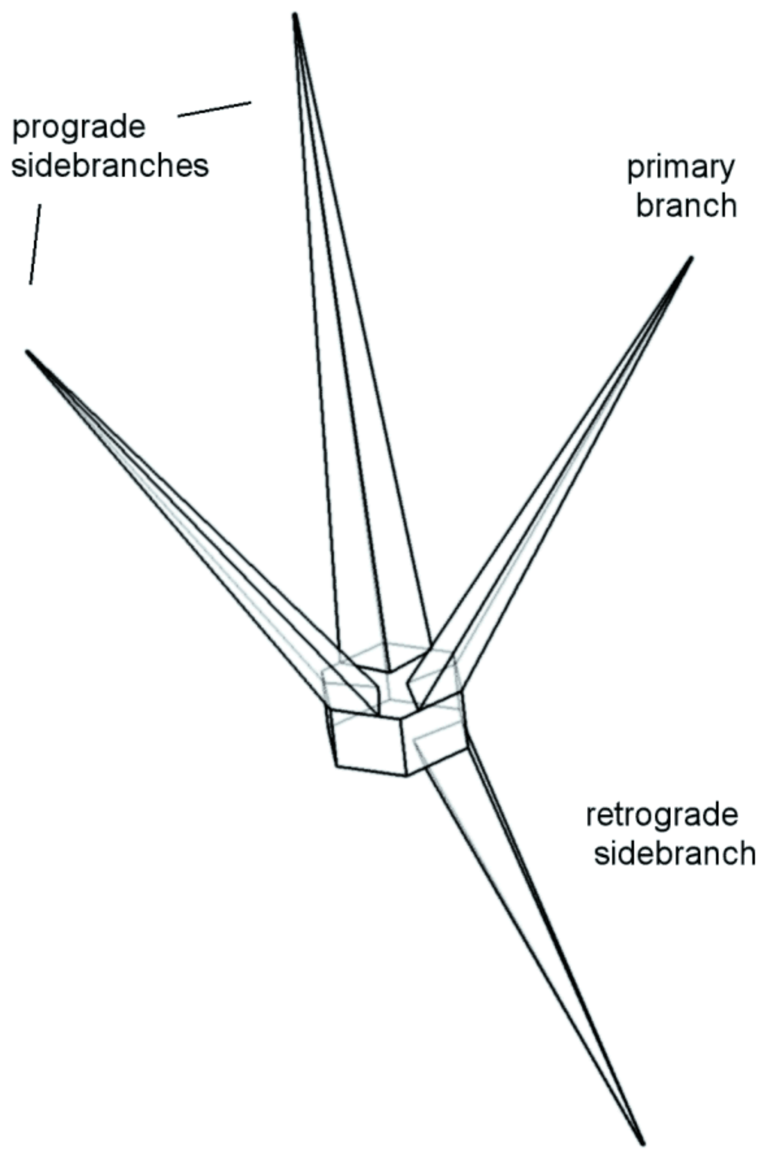

Figure 5: A single "vertebra" in our model of fishbone dendrites. The hexagonal prism is exaggerated and drawn mainly to establish the crystal axes. Three "spires" grow from the top of the prism, along with a single spire growing out from the bottom of the prism. Projected onto the basal plane, each spire grows along a crystalline a-axis. The angles between the spires and the c-axis are a function of the local temperature and supersaturation. This vertebra includes three main free parameters – the angles between the c-axis and each of: the primary spire, the retrograde spire, and the prograde spires.

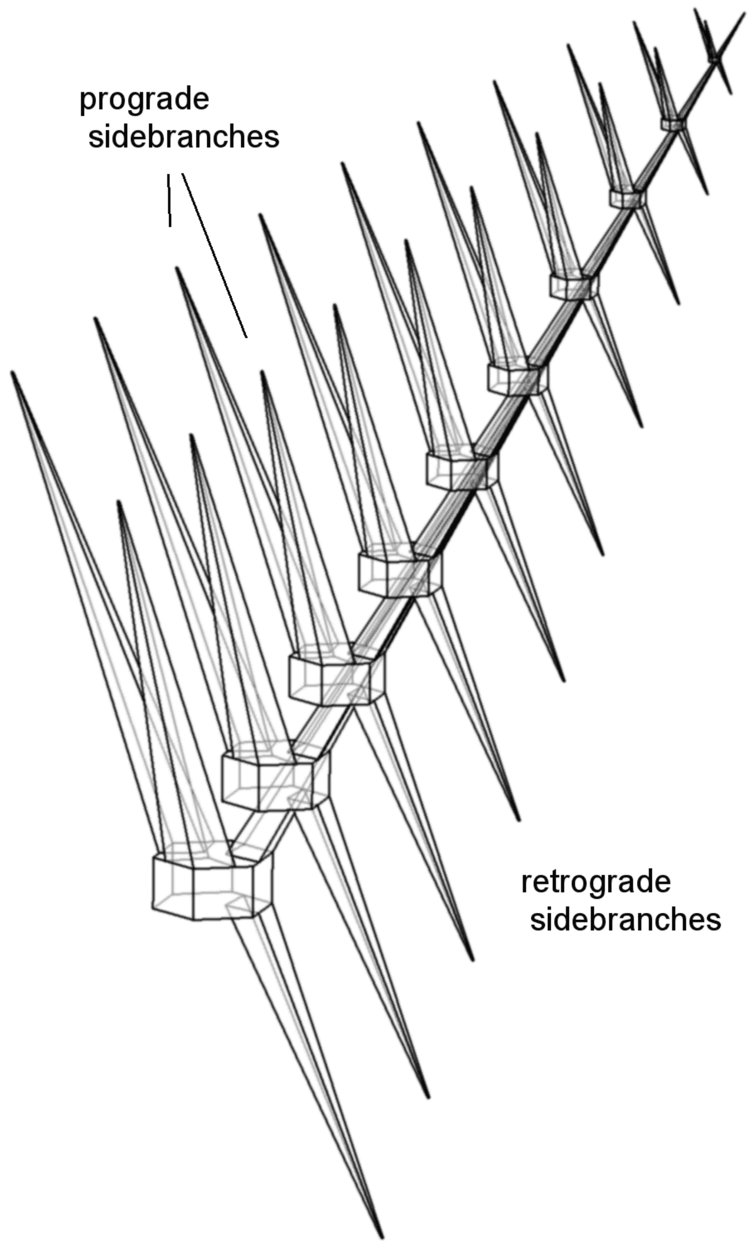

Figure 6: Assembly of several “vertebrae” into a growing fishbone dendrite. Again the hexagonal prisms are drawn mainly to indicate the crystal axes; they are not meant to be a visible part of the final structure. This geometric model should be compared with the actual ice dendrite shown in Figure 2.

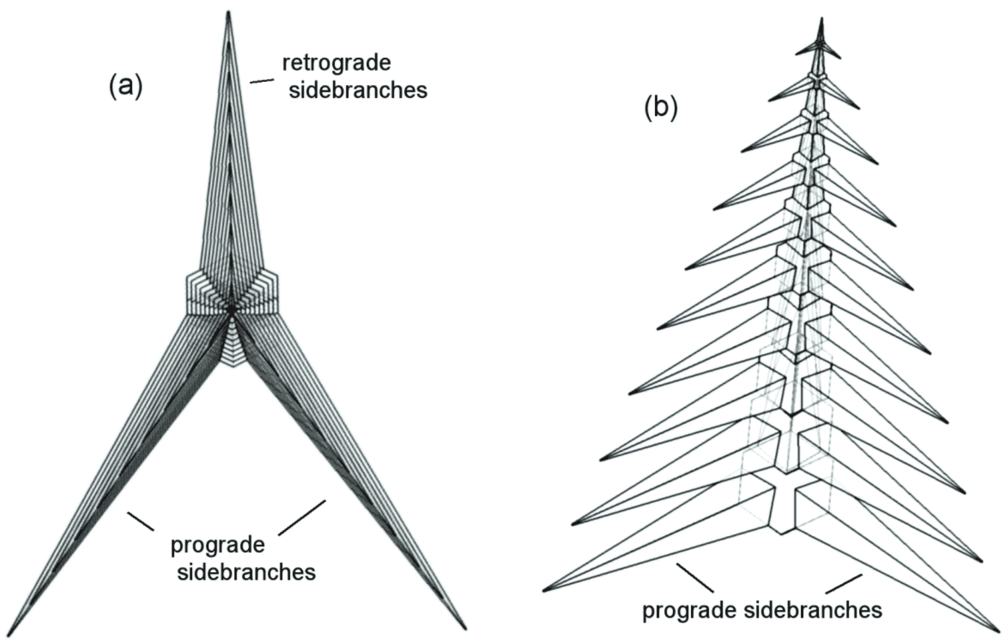

Figure 7: (a) The view straight down the primary branch. The angle subtended by the two sets of prograde sidebranches depends on growth conditions. Near -5 C, we found that this angle increases with increasing supersaturation. (b) The view down the c-axis. From this viewing direction the projected angle between the two sets of prograde sidebranches is 120 degrees, as are the angles between the prograde sidebranches and the primary branch. Regardless of the particular growth directions of the different branches and sidebranches (which depend on temperature and supersaturation), it is always possible to find a viewing angle that exhibits this 120-degree symmetry.